

# Ensemble Prediction of Tropical Cyclone Tracks from NTHF, SisPI and SPNOA Systems

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**Abstract:** Tropical cyclones are extreme hydrometeorological events whose impact causes human, material and economic losses. The inaccuracies in the forecast of the trajectory of these phenomena often lead to inefficient decisions, such as unnecessary evacuation. This research proposes the combination of the three forecasting tools NTHF, SisPI and SPNOA in the generation of ensemble prediction systems, with the aim of improving the track forecasts of tropical cyclones. Three variants were used for the construction of time-lagged ensembles, and for their evaluation the best track and historical errors (2016-2020) of the National Hurricane Center (NHC) were used. The ensembles lead to an improvement in tropical cyclone track forecasts. Position errors vary from case to case, but ensembles generally tend to be more accurate than independent forecasts. Compared to the historical errors of the NHC, the results obtained are promising because they are superior in some cases.

**Keywords:** ensemble prediction system; tropical cyclones; numerical weather forecast models

## 1. Introduction

Cuba is hit by extreme weather events, with tropical cyclones (TCs) being the most closely watched due to their frequency and destructive potential. That is why the forecast of TCs constitutes a task of importance and these are carried out on the basis of operational numerical models [1].

Despite the improvement achieved, numerical weather prediction models are still far from perfect and continue to fail in some important weather situations. In recent decades, new techniques have been incorporated to reduce the limitations and uncertainties of the models, Ensemble Prediction Systems (EPSs) are a very powerful tool that allow overcoming some of these. EPSs attempt to sample the most important sources of error that deterministic numerical prediction models may suffer. By simulating these errors, they offer explicit and detailed information on the uncertainty of a weather forecast, as well as the most likely outcome of the predicted process [2].

Several have been the authors who have carried out studies at the international level to improve the track forecasts of TCs from EPSs. Zhang and Krishnamurti [3, 4] used a perturbation method based on empirical orthogonal functions and applied this technique to a global spectral model. Goerss [5] and Lee and Leung [6] evaluated the performance of the multi-model technique, the sets proposed in both investigations were determined simply by averaging the forecast positions of the models used. Other investigations carried out showed superior results to the simple multi-model technique. For example, Kotal and Roy [7] and Jun [8] presented an unequal weighting technique applying the multiple linear regression and partial least squares regression techniques, respectively. Nishimura and Yamaguchi [9] applied a selective ensemble mean technique that excluded from the set of eleven models those that presented large position errors in short times.

Academic Editor: Anthony Lupo

Published: 20 July

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These investigations have shown that the resulting forecasts are, on average, significantly better than the individual forecasts of the models.

In Cuba this topic has not been addressed. Hence, it is considered necessary to propose the following research to achieve a forecast that is capable of reflecting reality as much as possible. The generation of EPSs is proposed from the combination of TC track forecasts from the Numerical Tools for Hurricane Forecast (NTHF), Short range Prediction System (SisPI) and Numeric Ocean-Atmosphere Forecasting System (SPNOA) systems. Three variants were used for the construction of time-lagged ensembles, and for their evaluation the best track and historical errors (2016-2020) of the National Hurricane Center (NHC) were used.

## 2. Methods

### 2.1. Operating systems in Cuba for forecasting tropical cyclones

At Institute of Meteorology (INSMET), the numerical prediction of TCs is carried out through two configurations derived from the Weather Research and Forecasting-Advanced Research Weather (WRF-ARW) model named SisPI and SPNOA. The SisPI's main objectives are the numerical forecast of meteorological events on a local scale and the quantitative forecast of precipitation. It has four daily initializations (0000, 0600, 1200 and 1800 UTC) of its forecast with a three-hourly update of lateral boundary conditions [10]. The SPNOA's fundamental objectives are the numerical forecast of TCs and the forecast of the state of the ocean in the inter-American seas and Cuban waters. It has two daily initializations (0000 and 1200 UTC) of its forecast with a three-hour update of lateral boundary conditions [11, 12].

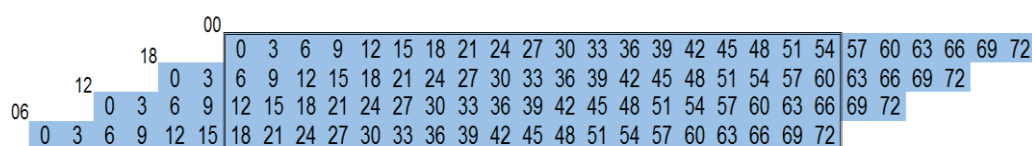
Another forecasting system used in the prediction of these meteorological phenomena in Cuba is NTHF, which has been implemented and is operational in the Department of Meteorology of the Higher Institute of Applied Technologies and Sciences (InSTEC) of the University of Havana. It has two daily initializations (0000 and 1200 UTC) of its forecast with an update of lateral boundary conditions every 6 hours [13, 14, 15].

### 2.2. Ensemble members

It is intended to use all available initializations of the forecast tools NTHF, SisPI and SPNOA. The three systems are obtained from configurations derived from the WRF model, but each one of them presents different physics, domains, resolutions and parameterizations, which indicates that multi-physics and multi-parameter techniques are applied to combine the members.

In order to increase the number of members of the set, the time-lagged technique is also applied. The time-lagged technique is nothing more than a combination of the current forecast with previous forecasts [16].

A schematic representation is shown in Figure 1, where four daily runs with initialization 0000, 0600, 1200 and 1800 UTC can be viewed, with the 0000 UTC run being the most updated. If m00, m06, m12 and m18 are denoted as the members of a set defined by the runs of 0000, 0600, 1200 and 1800 UTC respectively, then given the scheme, for the first 54 hours of forecast of m00, it is also counted with the forecast of the 60, 66 and 72 hours of the members m18, m12 and m06, that is, the set is made up of four members for that range of hours.



**Figure 1.** Scheme that exemplifies the ensemble prediction method based on initializations with different runs.

Once the members were defined, three variants were used to combine them and obtain the ensembles: mean, weighted mean and selective mean.

### 2.3. Study cases

The case studies selected for this research are presented in Table 1. For the evaluation of the three tools, all the available initializations of the seven TCs were used, but for the construction of the EPSs only the Irma and Eta systems were chosen by two aspects: they are TCs that affected Cuban territory in recent years and existence of sufficient information from the three forecast systems for the construction of the EPSs.

**Table 1.** Case studies used in the research.

Irma (September 2017)	Fred (August 2021)
Laura (August 2020)	Grace (August 2021)
Eta (November 2020)	Ida (August 2021)
Elsa (July 2021)	

## 3. Results and discussion

### 3.1. Evaluation of the forecasting tools NTHF, SisPI and SPNOA

To carry out a general evaluation of the performance of the three systems in the track forecast, all the available initializations of the TCs represented in Table 1 were used. The distances (in km) at which the predicted trajectories are found with respect to the NHC best track were calculated for different time periods.

Table 2 shows a comparison between the results obtained from the evaluations of the three systems and the mean forecast errors of the NHC for the years 2016-2020. It can be seen that the ability of NTHF is high, especially for periods of up to 48 hours, however, discrete results are obtained for longer periods. In the case of the SisPI, the forecasts are effective in the first 12 hours, while for other periods the errors grow notably. This is due to, among other reasons, the fact that this system was not properly designed for this type of forecast. In the results of these two tools, it is possible to observe the tendency of forecast errors to grow with time periods, a situation that does not occur with the SPNOA, since it shows a decrease after 36 hours, the cause of this behavior is not known, but it is consistent with other evaluations carried out by the developers of the SPNOA [12]. In summary, for the first 12 hours the best results are reported by the NTHF and SisPI, between 24 and 48 hours the forecasts of the NTHF and SPNOA are more precise and for longer periods those of SPNOA are the most effective. The superior performance of the NTHF is to be expected since it was built especially for TC forecasting and tracking. In addition, it incorporates the vortex tracking technique, which guarantees that the interior domain is always centered on the TC in such a way that it better reproduces its movement and physical-dynamic characteristics.

**Table 2.** Position errors (km) in the track forecast of the NTHF, SisPI and SPNOA systems.

	0 h	12 h	24 h	36 h	48 h	60 h	72 h
NHC	11.59	38.14	58.26	78.86	102.68	134.86	151.60
NTHF	15.82	66.56	83.40	111.86	142.450	221.11	328.16
SisPI	44.60	54.08	140.50	190.90	231.69	297.05	337.83
SPNOA	40.35	122.87	133.07	150.63	149.88	175.14	235.81

For the construction of the weighted mean ensemble, it was necessary to generate different weights to be assigned to each of the members and for this the general evaluation carried out was used.

In Table 3 it can be seen that the weights vary according to the performance of each tool in the trajectory forecast. Initially NTHF and SisPI are the ones with the greatest weight and this is due to the fact that in the first 12 hours they report more accurate forecasts, for time periods between 24 and 48 hours the NTHF and SPNOA predictions have greater value and finally the SPNOA forecasts are the most effective for that reason are attributed greater weights.

**Table 3.** Weights for the corresponding members of the NTHF, SisPI and SPNOA.

	0 h	12 h	24 h	36 h	48 h	60 h	72 h
NTHF	0.99	0.97	0.97	0.95	0.94	0.91	0.87
SisPI	0.98	0.98	0.94	0.92	0.91	0.88	0.86
SPNOA	0.98	0.95	0.95	0.94	0.94	0.93	0.90

A more specific evaluation was also carried out by initializing the forecast systems used. The tables show the results obtained.

From Table 4 it can be seen that NTHF 0000 UTC initializations tend to be more effective than 1200 UTC. Table 5 shows that for the first 12 hours the initializations at 1200 and 1800 UTC present fewer errors, but the same does not happen for longer periods where 0000 and 0600 UTC stand out. In Table 6 it can be seen that the SPNOA 0000 UTC initializations are much more accurate than those of 1200 UTC. In general, it can be summarized that for the initialization of 0000 UTC, the NTHF presents a superior behavior to the other two tools in the first 12 hours, but in longer periods, the SPNOA presents fewer errors. On the other hand, in the first 48 hours of the initialization of 1200 UTC, the NTHF forecasts with less error, and again for the other timeframes the SPNOA has more accuracy.

**Table 4.** Position errors (km) in the track forecast of the two NTHF initializations.

Initialization	0 h	12 h	24 h	36 h	48 h	60 h	72 h
0000 UTC	15.21	51.45	73.11	111.30	140.06	224.07	320.15
1200 UTC	18.49	68.37	101.15	126.71	162.67	231.05	330.65

**Table 5.** Position errors (km) in the track forecast of the four SisPI initializations.

Initialization	0 h	12 h	24 h	36 h	48 h	60 h	72 h
0000 UTC	44.38	53.28	100.80	186.51	199.36	238.17	305.23
0600 UTC	58.10	58.79	114.43	169.15	219.45	264.54	303.79
1200 UTC	38.34	51.24	132.08	158.08	201.85	295.81	347.09
1800 UTC	37.99	53.18	209.67	247.86	298.13	388.37	396.58

**Table 6.** Position errors (km) in the track forecast of the two SPNOA initializations.

Initialization	0 h	12 h	24 h	36 h	48 h	60 h	72 h
0000 UTC	43.96	62.35	67.19	92.87	124.44	163.01	211.17
1200 UTC	36.40	181.71	198.95	210.18	178.16	190.66	264.94

This evaluation was carried out with the aim of obtaining the members used in the construction of the third ensemble. A schematic representation is shown in Figure 2, where the elements that make up the members can be viewed when the NTHF, SisPI and SPNOA initializations are available. Members m06 and m18 will be those of the SisPI as it is the only tool that has runs at these times and members m00 and m12 will be a combination depending on the behavior of the systems by section.

0 h	12 h	24 h	36 h	48 h	60 h	72 h
m00nthf	m00nthf	m00spnoa	m00spnoa	m00spnoa	m00spnoa	m00spnoa
m18sispi	m18sispi	m18sispi	m18sispi	m18sispi	m18sispi	m18sispi
m12nthf	m12sispi	m12nthf	m12nthf	m12nthf	m12spnoa	m12spnoa
m06sispi	m006sispi	m06sispi	m06sispi	m06sispi	m06sispi	m06sispi

**Figure 2.** Members used in the construction of the selective set when the initializations of the NTHF, SisPI and SPNOA are available.

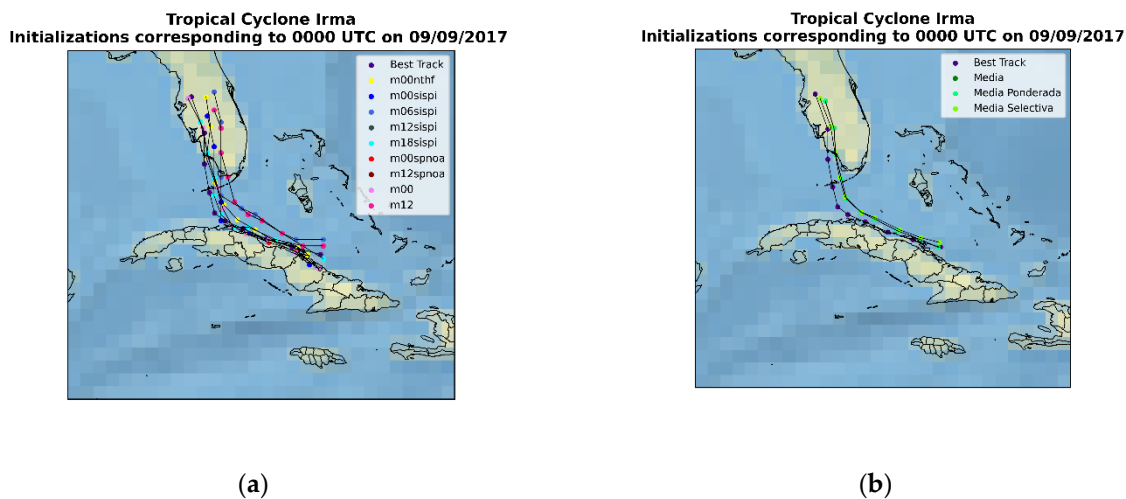
3.2. Performance of the proposed ensemble prediction systems

3.2.1. Tropical Cyclone Irma

Irma affected Cuba as a hurricane on September 8 and 9, 2017. The three ensembles proposed for September 9 at 0000 UTC were built. According to the best track, on September 9 at 0000 UTC, Hurricane Irma was at north of Nuevitas and then moved west-northwest, bordering the north coast from Camagüey to Matanzas, throughout the 9<sup>th</sup>. The following day, the system began to move north, in direction of the Florida peninsula.

In Figure 3 (a) it can be seen that in the first 24 hours of the forecast, most of the employed members had a very similar behavior among themselves and even closely resembled the best track. After 24 hours, the trajectories began to diverge. Most predicted a slower moving hurricane, but it stayed on the same track, moving first west-northwest and then north.

Figure 3 (b) represents a comparison between the three ensemble forecasts obtained and the best track. It can be seen that in the first 18 hours of the forecast, the behavior of the groups is very similar to the official trajectory of Irma, but for longer periods they move away a little. Again, the results incorrectly predicted Irma's translational speed, but matched the system's heading.



**Figure 3.** Tropical Cyclone Irma: Initializations corresponding to 09/09/2017 at 0000 UTC (a) Employed Members; (b) Obtained ensembles.

In order to have a better representation of the results obtained, the distances (km) at which the trajectories obtained are found with respect to the best track were calculated. Table 7 shows the ensemble errors and historical NHC error over the years 2016-2020 and the official NHC errors for the Irma forecast. It can be seen that all three ensembles were accurate, although in the first 36 hours the second and first ensembles reported smaller errors and then the results of the third ensemble were more effective. This situation is due to the fact that initially the employed members have a greater consensus and that is why the mean and the weighted mean report more accurate forecasts, but later the members

begin to disagree and it is then that the selective mean excels in the forecast. Compared to the NHC, it can be seen that the mean and weighted mean ensembles were accurate throughout the forecast period, while the selective mean ensemble initially forecasts with less accuracy but after 12 hours reports significantly lower errors. This is explained because, in this case, the members used in the ensembles had greater skill than the NHC forecasts, hence the decrease in errors in the ensembles.

**Table 7.** Position errors (km) in the track forecast of the sets obtained for 09/09/2017 at 0000 UTC.

	Mean	Weighted mean	Selective mean	NHC (Irma)	NHC (2016-2020)
0 h	8.48	8.89	21.36	-	11.59
12 h	35.72	35.55	44.75	23.82	38.14
24 h	51.51	51.29	53.85	41.04	58.26
36 h	51.79	51.64	53.78	60.51	78.86
48 h	34.50	33.86	30.39	81.27	102.68

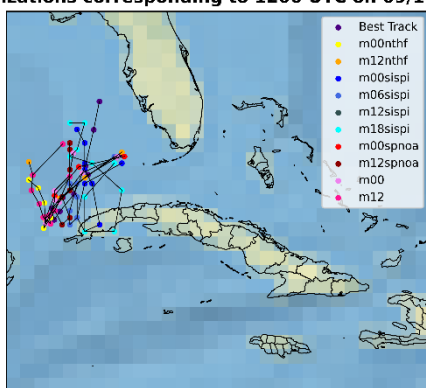
### 3.2.2. Tropical Cyclone Eta

Eta affected Cuba as a tropical storm on November 8 and 10, 2020. The three ensembles proposed for November 9 at 1200 UTC were built. According to the best track, on November 9 at 1200 UTC, tropical storm Eta was located west of the Florida peninsula. It then moved southwest until 0600 UTC on November 10. That same day, the system made a cyclonic loop and on the 11th it began a movement towards the north.

Note, in Figure 4 (a), that not all members predicted the cyclonic loop and some of those who did predict it elsewhere. After the loop, all members forecast a slower movement of the cyclone. Another detail was that many members failed to forecast the northerly course that the system assumed when the loop ended, most forecasting a northwestward motion. In general, it can be said that, in the case of Eta, in this section of its life cycle, the consensus among the members was lower, compared to the case previously studied.

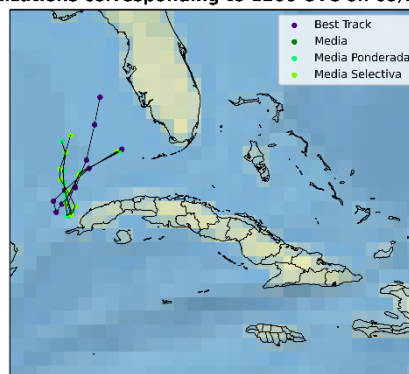
In Figure 4 (b) it can be seen that in the first 6 hours, the ensemble forecasts resemble the best track. The three trace the cyclonic loop, although not exactly in the same place, they are a little closer to Pinar del Río. After the loop, all three ensembles forecast a slow northward movement of the cyclone.

**Tropical Cyclone Eta**  
Initializations corresponding to 1200 UTC on 09/11/2020



(a)

**Tropical Cyclone Eta**  
Initializations corresponding to 1200 UTC on 09/11/2020



(b)

**Figure 4.** Tropical Cyclone Irma: Initializations corresponding to 09/11/2020 at 1200 UTC (a) Employed Members; (b) Obtained ensembles.

From Table 8 it can be identified that the weighted mean and the mean performed very well up to 36 hours, but in longer terms the errors grew considerably. Compared to the historical errors of the NHC, it can be seen that in the first 36 hours the sets performed very well, being more effective.

**Table 8.** Position errors (km) in the track forecast of the sets obtained for 11/09/2020 at 1200 UTC.

	Mean	Weighted mean	Selective mean	NHC (Irma)	NHC (2016-2020)
0 h	16.76	16.62	21.77	-	11.59
12 h	42.93	42.70	54.09	40.56	38.14
24 h	71.73	70.37	85.55	67.91	58.26
36 h	45.88	45.24	63.98	103.48	78.86
48 h	133.26	135.22	136.58	146.45	102.68

#### 4. Conclusions

In the present investigation, three alternatives were implemented to improve the forecast of the trajectory of TCs from the combination of the NTHF, SisPI and SPNOA tools. The analysis of the results led to the following conclusions:

1. The evaluation of the NTHF, the SisPI and the SPNOA, for the cases studied, showed that in the first 48 hours the NTHF tends to be more precise, but in longer periods the SPNOA stands out.
2. The mean and weighted mean variants were the ones that reported the least errors in the initial terms and in the last forecast hours, the selective mean stands out. This is due to that in the first hours there was a greater consensus among the employed members, and for this reason the mean and weighted mean are more effective. With increasing uncertainty over time, members begin to disagree, and so the selective mean is more accurate.
3. The degree of improvement of ensembles varies from case to case, but in general they tend to be more accurate than independent forecasts. Regarding the historical errors of the NHC, it can be concluded that the results are promising because they are better in some cases.

**Author Contributions:** Conceptualization, L.F.J. and M.S.L.; methodology, L.F.J. and M.S.L.; software, L.F.J. and M.S.L.; validation, L.F.J. and M.S.L.; formal analysis, L.F.J. and M.S.L.; investigation, L.F.J.; resources, L.F.J. and M.S.L.; data curation, M.S.L.; writing—original draft preparation, L.F.J.; writing—review and editing, L.F.J. and M.S.L.; visualization, L.F.J. and M.S.L.; supervision, M.S.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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